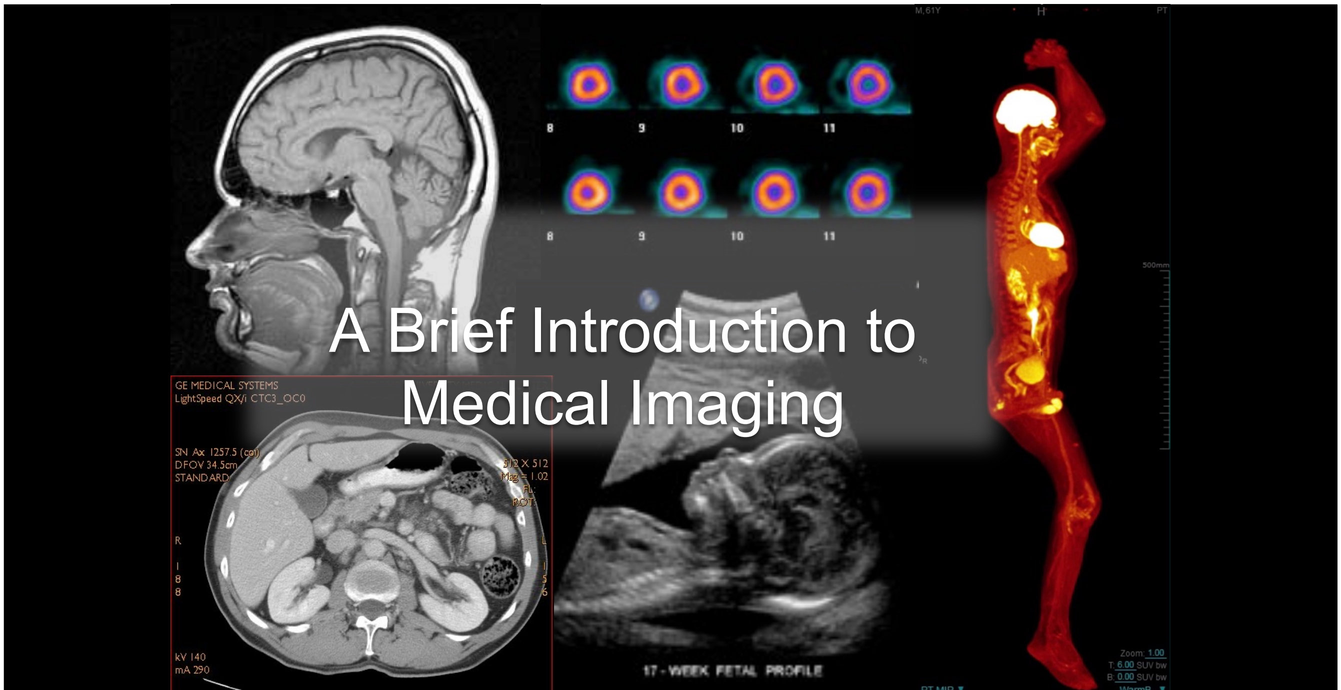


# A Brief Introduction to Medical Imaging



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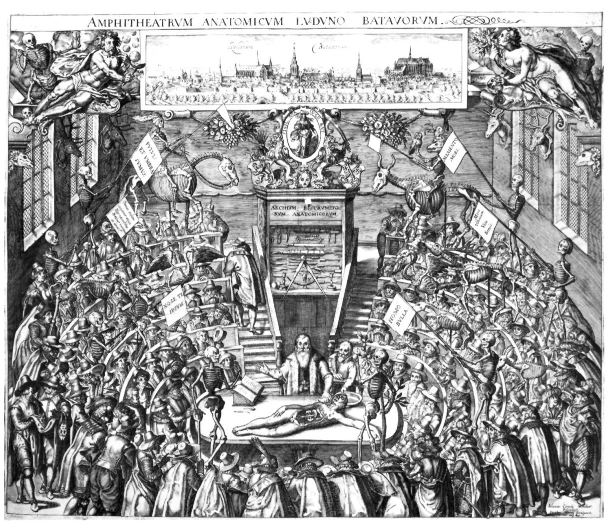
## BEFORE MEDICAL IMAGING

Knowledge of structure and function of the human body in health and disease limited to

external observation

studies of blood and urine

detailed post-mortem dissection




*Theatrum anatomicum in Leiden, copperplate engraving ~1615*



2

# NOVEMBER 8th,1895: DISCOVERY OF X-RAYS

Wilhelm Röntgen

First image
Dec 21st , 1895

EINE NEUE ART

VON

STRAHLEN.

VON

DR. W. RÖNTGEN,

WÜRZBURG.

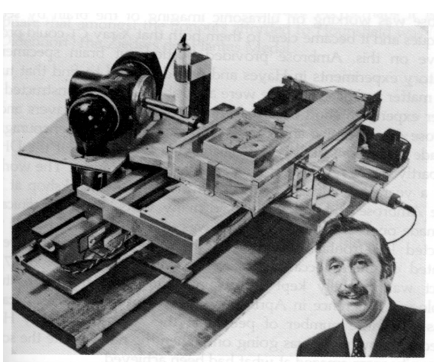
First paper on X-rays,
published Dec 28th, 1895

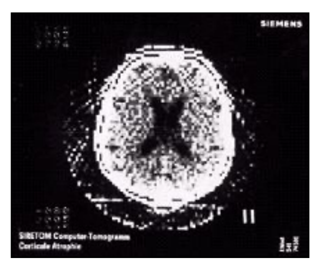


3

# 1971: COMPUTED TOMOGRAPHY (CT) SCANNER

## GODFREY HOUNSFIELD






Early CT scan
~1975

Other key contributers to tomography include
Johann Radon, William Oldendorf and Allan Cormack



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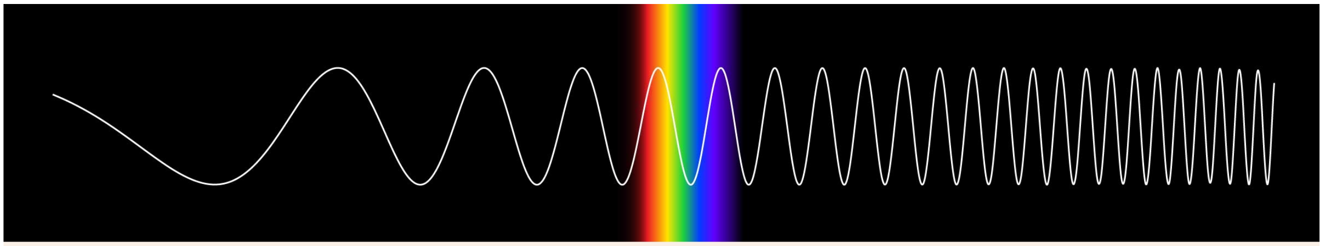
# RADIATION USED FOR IMAGING



RADIO | MICROWAVE | INFRARED | VISIBLE | ULTRAVIOLET | X-RAY | GAMMA RAY

- RADIO: MRI
- Ultrasound
- X-RAY: X-ray, Mammography, Fluoroscopy, CT
- GAMMA RAY: Nuclear Med, SPECT, PET

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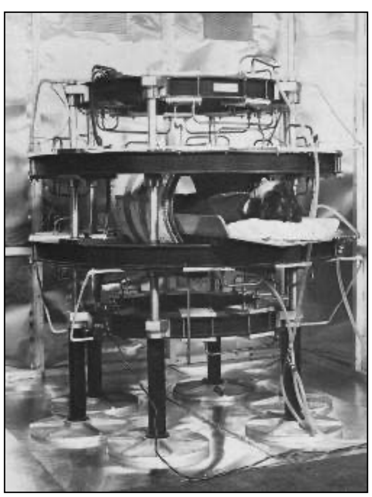
# MEDICAL IMAGING: FROM PHYSICS TO SYSTEMS



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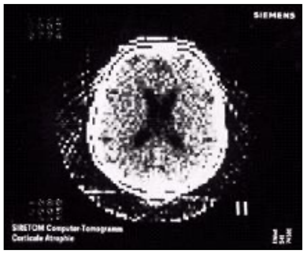
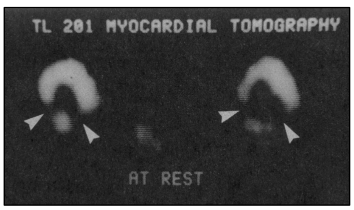
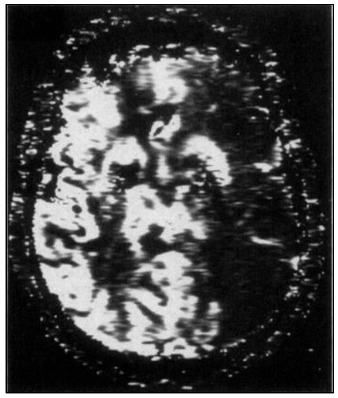
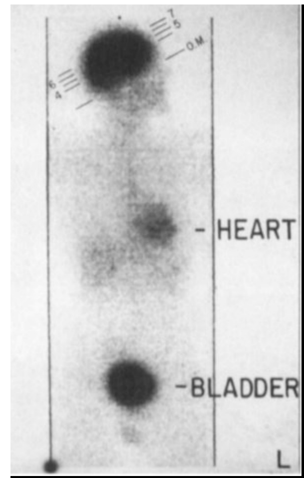
# MEDICAL IMAGING: EARLY IMAGES





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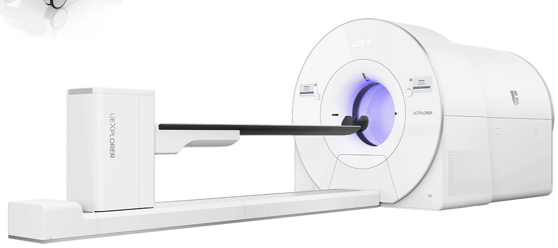
# MEDICAL IMAGING: ENGINEERING REVOLUTION





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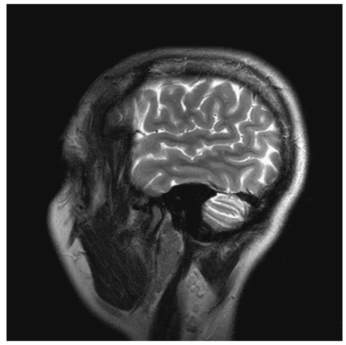
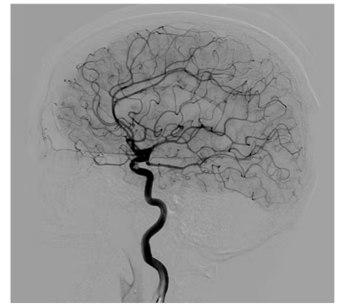
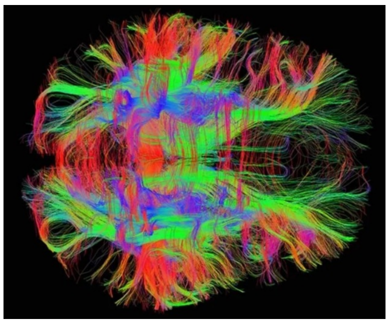
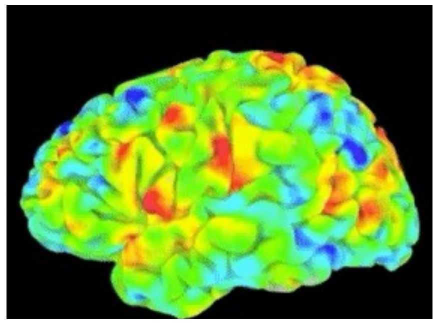
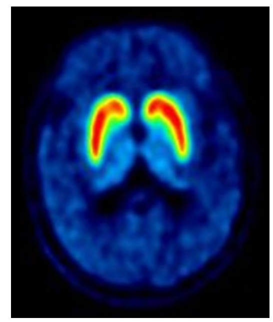
# MEDICAL IMAGING
# BRAIN





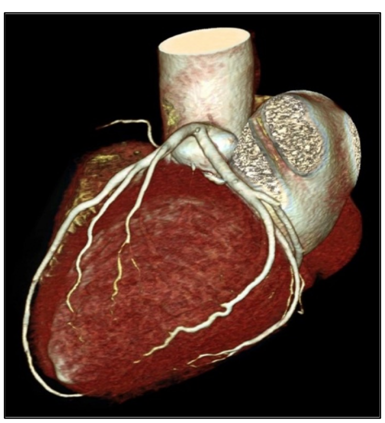


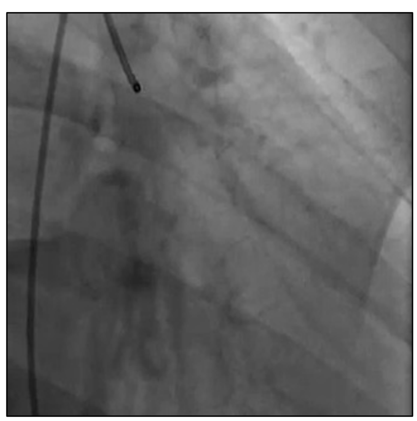


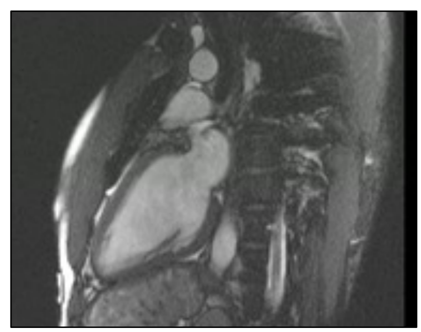


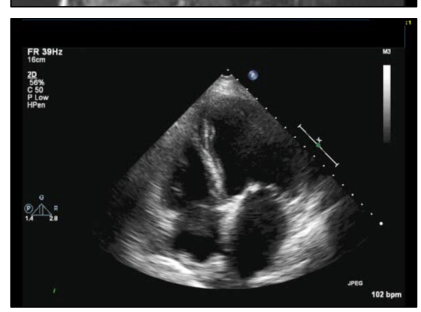


# MEDICAL IMAGING
# HEART

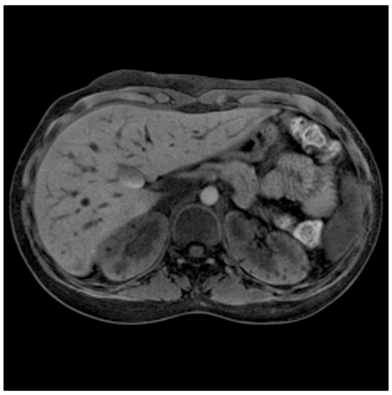








## MEDICAL IMAGING
# ACROSS THE BODY





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# How Do Imaging Modalities Differ?

- What do they measure
- Spatial scale of measurement
- Temporal scale of measurement
- Sensitivity of measurement
- Field of view of measurement
- Cost of measurement
- Hazard/risk associated with measurement



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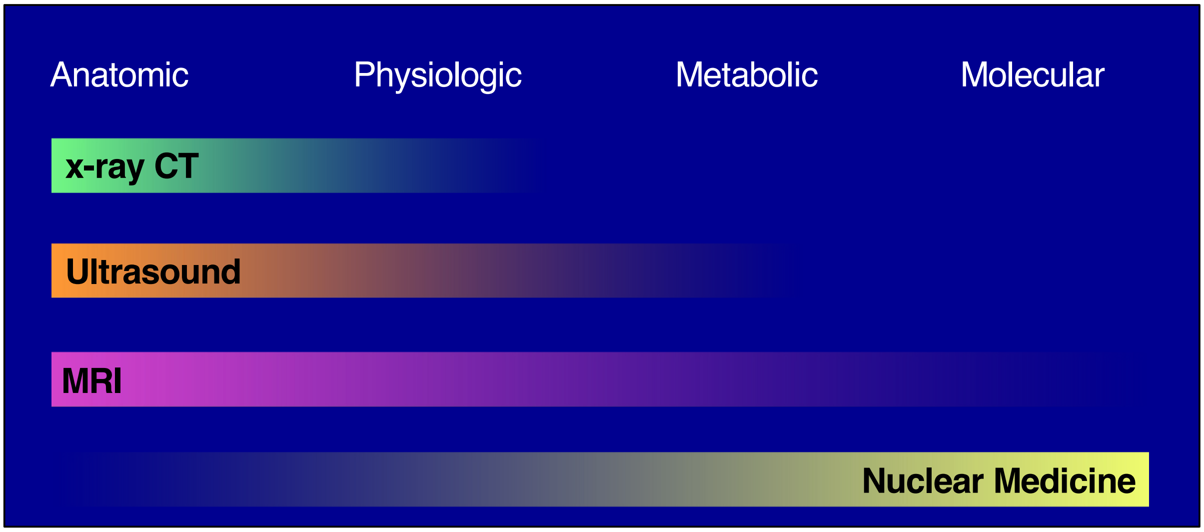
# Biomedical Imaging



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# Impact

- Medical imaging plays a role in the assessment of virtually every injury and many forms of disease.
- ~ 400 million medical imaging procedures per year in the U.S.A.
- Medical imaging has improved diagnosis and saved many lives



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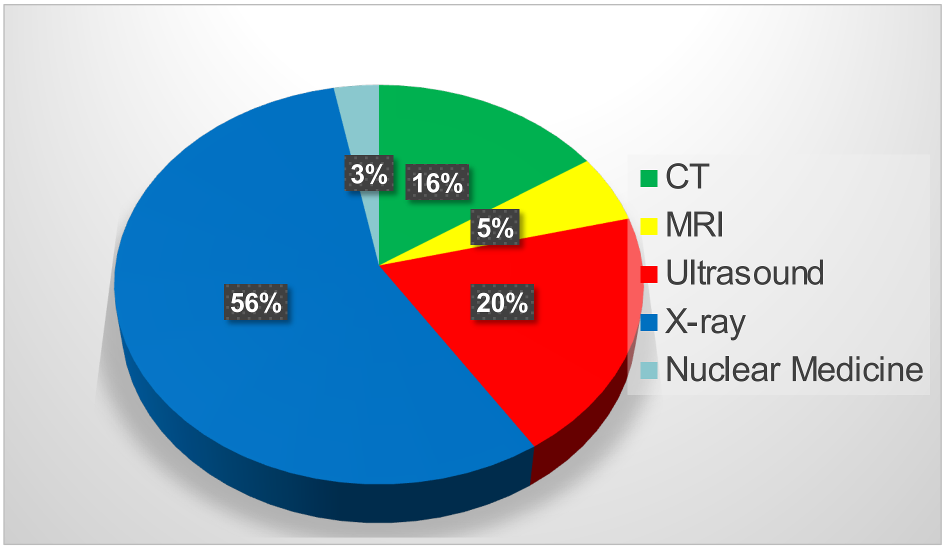
# Utilization




Global market
~$25B (2017)



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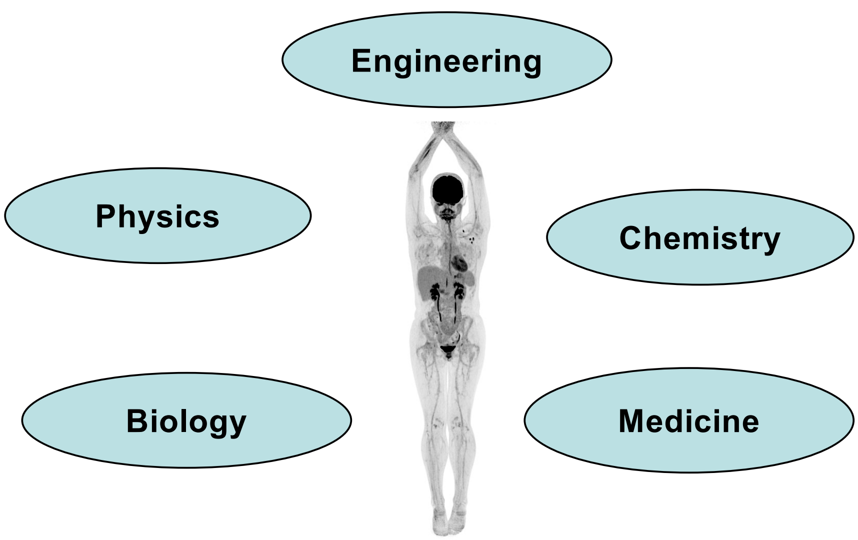
# Medical Imaging is a Multidisciplinary Field



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# Careers in Biomedical Imaging

- Industry
  - Medical Imaging Companies
    - Siemens, GE, United Imaging, Philips etc…
  - Pharmaceutical/Biotech Companies
    - Genentech, Merck, Pfizer, Novartis etc…
  - Contract Research Organizations
    - Invicro, Imaging Endpoints, etc…
  - Detector companies
    - Hamamatsu, Broadcom,…
  - Software companies (AI!)
    - Mirada, Subtle Medical, Amira…





# Careers in Biomedical Imaging contd…

- Academia/Education
  - Research
  - Teaching
- Hospitals/Medicine
  - Radiology (Med School first!)
  - Medical physics/engineering
- Other…
  - Funding agencies
  - Patent Office
  - Scientific publishing/journals
  - Scientific consulting

## Societal Issues for Biomedical Imaging

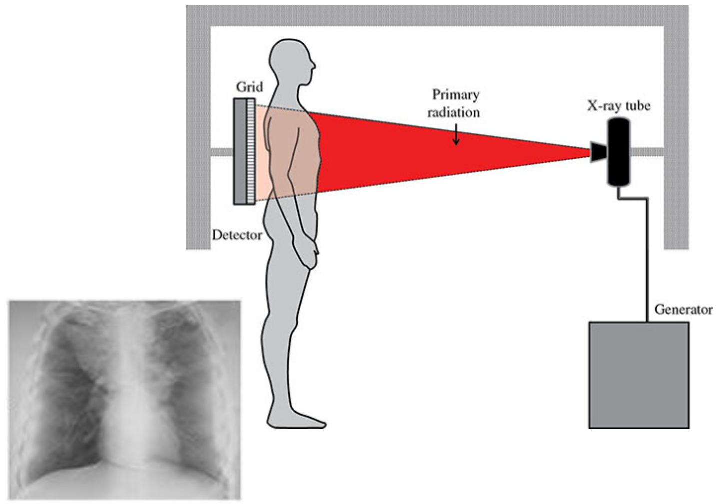
- $$$ Cost
- Equitable access
- Radiation dose (where applicable)
- Total body screening – overdiagnosis/treatment?
- Diagnosis in absence of treatment



## X-Ray Imaging

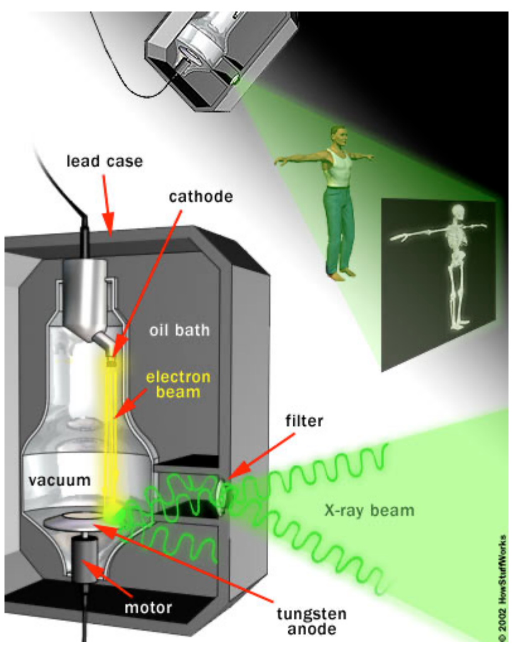

# General Principles

- Transmission-based technique
- X-rays pass through patient and detected by film or detector
- Contrast arises from differential attenuation of X-rays in body
- Planar radiography, image is a 2-D projection of tissues lying between x-ray source and detector




https://radiologykey.com/projection-x-ray-imaging/

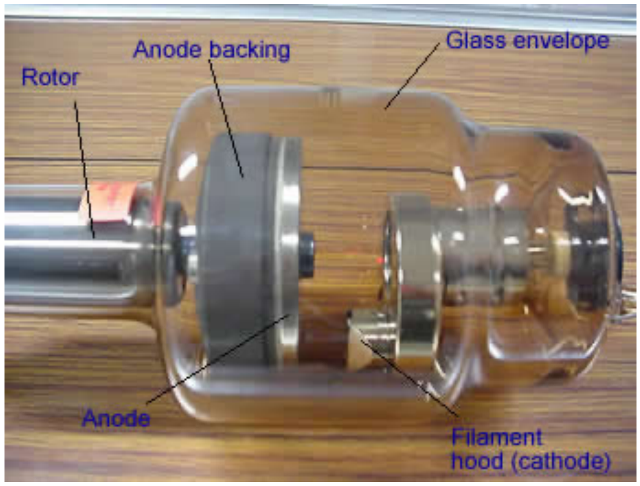





# X-Ray Tube

- Electrons produced by heating a filament (cathode) to ~2200° C - *thermionic emission*
- Electrons accelerated in an electric field (15-150 kV) and strike tungsten anode
- Electron interacting in tungsten target produces x-rays, that pass through exit window and filter
- Anode rotates

# X-Ray Tube






# X-Ray Energy

1 eV is the energy gained by an electron when it is accelerated through a potential difference of 1 V.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ joules}$$

In an x-ray tube, if the potential applied to the tube is 50 kV (50,000V), then the maximum energy x-ray that can be produced is 50 keV

The peak voltage applied to an x-ray tube is often designated as kVp

# X-Ray Tube Current and Output

- Flow of electrons between anode and cathode represents a current
- Tube current typically 50-400 mA
- Tube output (power) = tube current x applied voltage



# Efficiency of X-Ray Production

Incident power on anode is:

$P_i = V \times I$

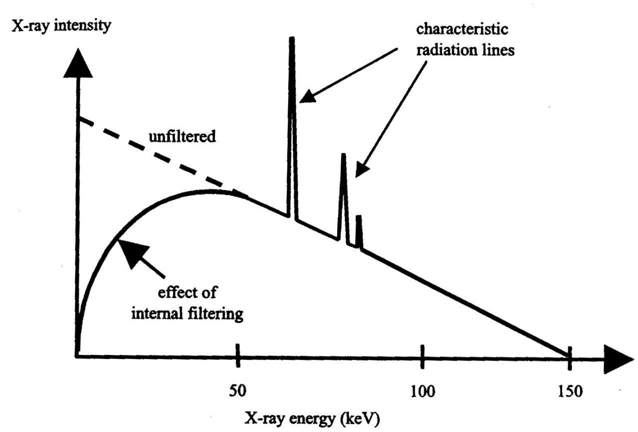
The radiated power is given by

$P_r = 0.9 \times 10^{-9}\, Z\, V^2\, I$

Efficiency = $\frac{P_r}{P_i} = 0.9 \times 10^{-9} ZV$ (only ~0.01% for tungsten!)

## X-Ray Spectrum

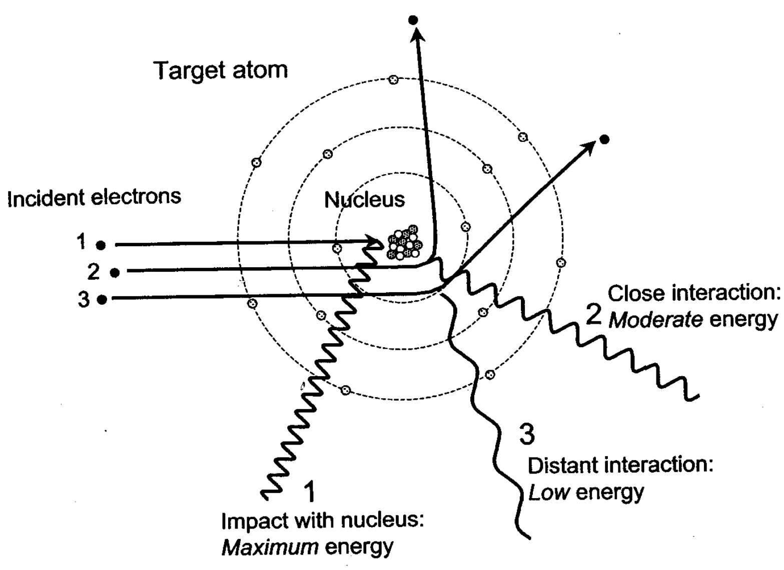
- Tube voltage = 150 kV
- Tungsten anode
- Two components
  - Continuous up to energy of 150 keV
  - Discrete lines



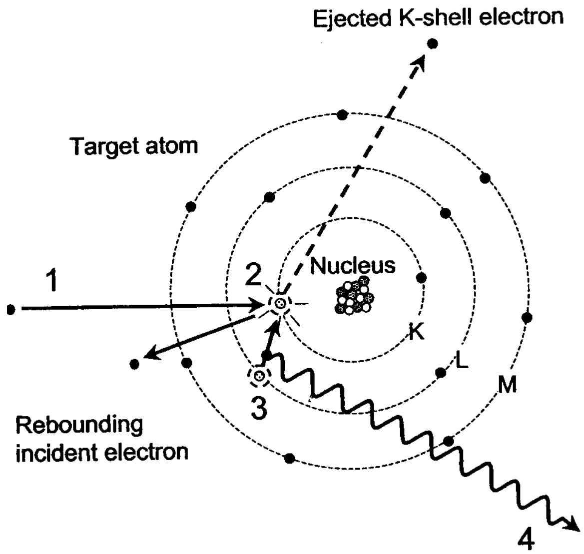





## Bremsstrahlung (continuous)



# Characteristic X-rays (discrete)






# Characteristic X-rays

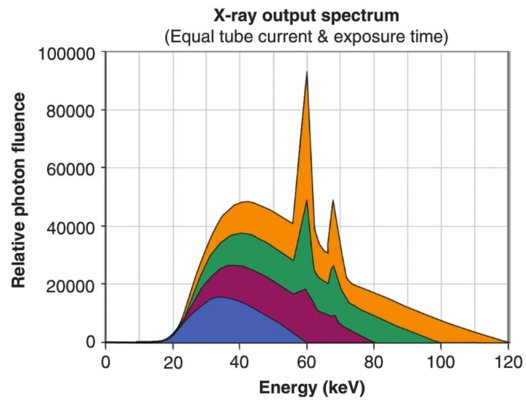
- Tungsten

**Table 3.1**
Principal Characteristic X-Ray Energies for Tungsten

| | Lines | Transition | Energy (keV) |
|---|---|---|---|
| K Series | $K\beta_2$ | $N_{III} - K$ | 69.09 |
| | $K\beta_1$ | $M_{III} - K$ | 67.23 |
| | $K\alpha_1$ | $L_{III} - K$ | 59.31 |
| | $K\alpha_2$ | $L_{II} - K$ | 57.97 |
| L Series | $L\gamma_1$ | $N_{IV} - L_{II}$ | 11.28 |
| | $L\beta_2$ | $N_V - L_{III}$ | 9.96 |
| | $L\beta_1$ | $M_{IV} - L_{II}$ | 9.67 |
| | $L\alpha_1$ | $M_V - L_{III}$ | 8.40 |
| | $L\alpha_2$ | $M_{IV} - L_{III}$ | 8.33 |

Data from U.S. Department of Health, Education, and Welfare. Radiological health handbook. Rev. ed. Washington, DC: U.S. Government Printing Office, 1970.

# Effect of Tube Voltage



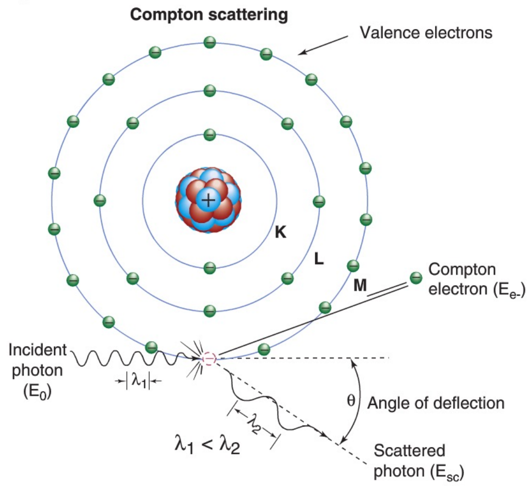

- Increases energy and number of x-rays
- Intensity proportional to square of tube voltage



# Interactions of X-Rays (and γ rays < 1 MeV) with Materials

- If x-rays interact, they can be absorbed or scattered from the x-ray beam
- Two main processes occur at x-ray energies
  – Compton Scattering
  – Photoelectric Effect
  – Coherent (Rayleigh) scattering has small probability
- In tissue these create contrast necessary for imaging, but also can lead to loss of information and radiation dose
- In detectors they are the basis for detecting x-rays

# Compton Scattering




- Probability roughly proportional to material density

$$E_o = E_{sc} + E_{e-}$$

$$E_{sc} = \frac{E_o}{1 + \frac{E_0}{mc^2}(1 - cos\theta)}$$



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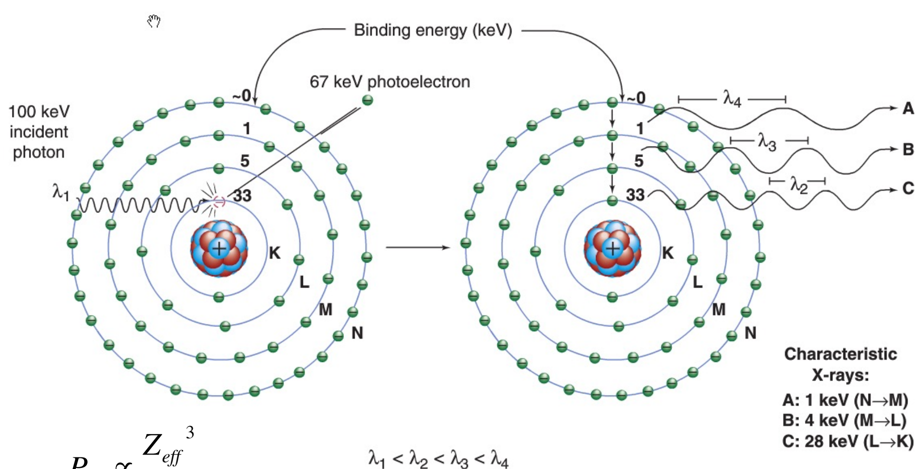
# Photoelectric Effect




$$P_{pe} \propto \frac{Z_{eff}^{3}}{E^3}$$



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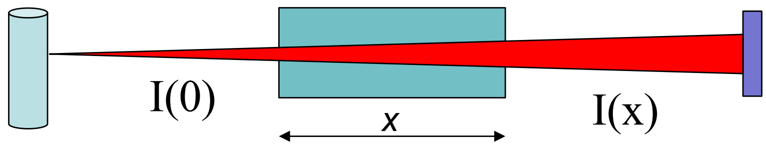
# Linear Attenuation Coefficient




- If a monoenergetic x-ray beam has intensity I(0) (photons per second per $cm^2$) before absorber, and intensity I(x) after passing through x cm of absorber, then the linear attenuation coefficient μ is defined as:

$$I(x) = I(0)e^{-\mu x}$$



# Attenuation Coefficient

- Sum of individual contributions from coherent and Compton scattering, and photoelectric absorption

$$\mu = \mu_{coherent} + \mu_{Compton} + \mu_{photoelectric}$$

- Half-Value Layer (HVL)
  - Thickness of tissue that attenuates x-ray beam by one half

$$HVL = (\ln 2) / \mu$$

# HVL for Different Energies

**TABLE 1.2. The Half-Value Layer (HVL) for Muscle and Bone as a Function of the Energy of the Incident X-Rays**

| X-ray energy (keV) | HVL, muscle (cm) | HVL, bone (cm) |
|---|---|---|
| 30 | 1.8 | 0.4 |
| 50 | 3.0 | 1.2 |
| 100 | 3.9 | 2.3 |
| 150 | 4.5 | 2.8 |

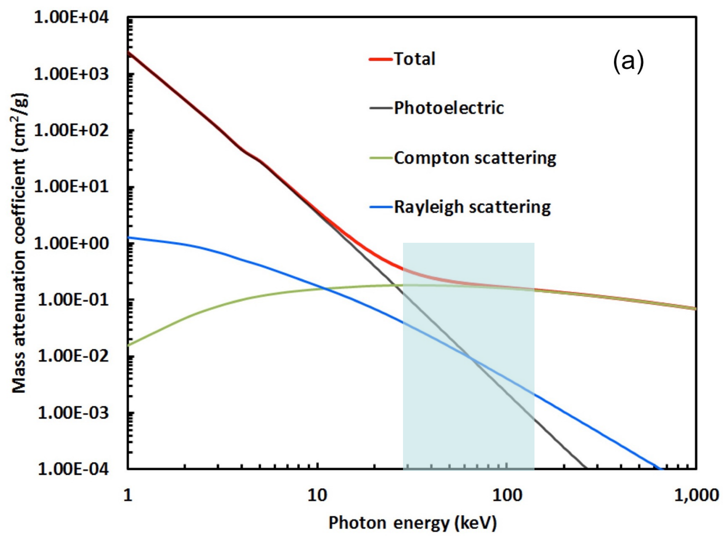


# Mass Attenuation Coefficient

- $\mu_m = \mu/\rho$
  - Units are $cm^2/g$
  - Useful, as it normalizes for density

$\mu_m = (\mu_{coherent}+\mu_{Compton}+\mu_{photoelectric})/\rho$

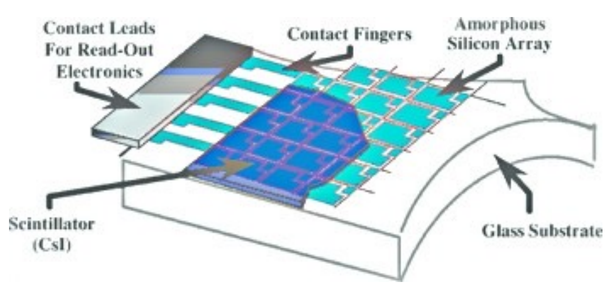
# Mass Attenuation Coefficients for Soft Tissue




Courtesy Dr. Kai Yang

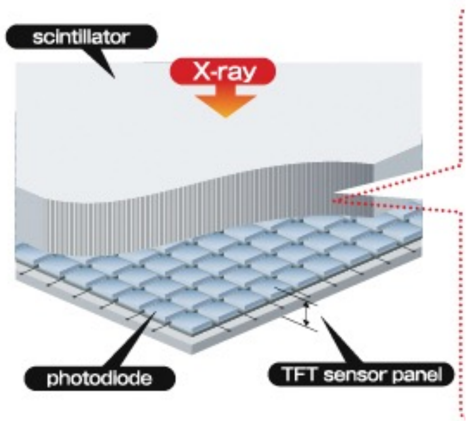


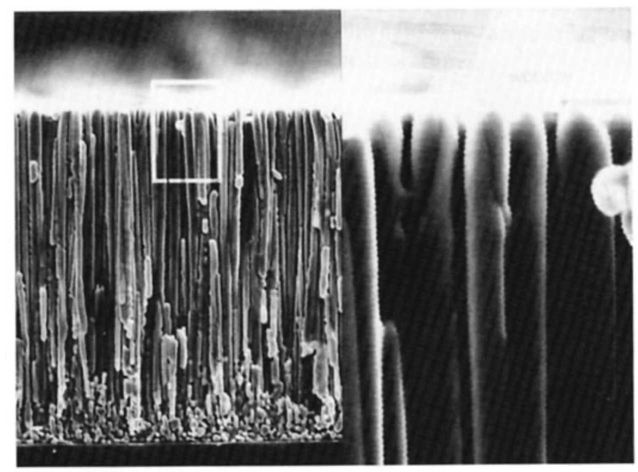
# Digital Radiography Detectors




- Large-area flat-panel detectors
- Amorphous silicon transistor array layered onto glass substrate (light detection and readout)
- CsI(TI) scintillator deposited on top (x-ray conversion)

## Structured CsI(Tl) Scintillator



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## Clinical X-ray Imaging System

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## X-Ray Contrast Agents

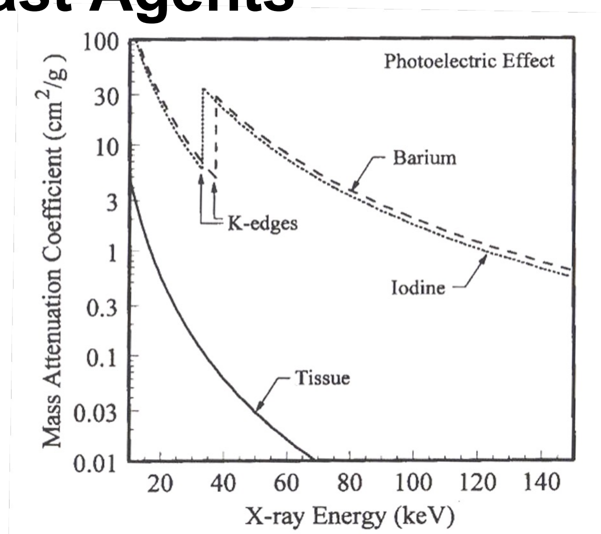
- Often intrinsic tissue contrast not sufficient to visualize disease
- Can introduce a “contrast agent” that increases contrast
- Contrast agent should be:
  - Non-toxic
  - Be composed of elements with an appropriate K-edge energy
    - barium (oral) and iodine (i.v.) are most common
  - Easy to administer (i.v., oral etc.)





## Attenuation Coefficients for Contrast Agents

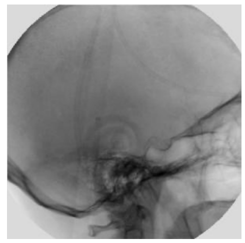
K-edge:
Barium 37.4 keV
Iodine 33.2 keV



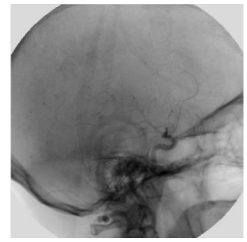
# X-Ray Angiography

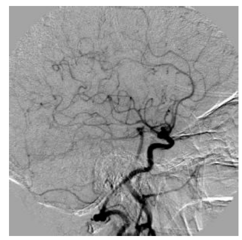
- Visualizes blood vessels
- Inject i-v intravascular contrast agent
- Digital subtraction angiography provides highest contrast by taking image before and after contrast agent administration
- Used for vascular problems, can resolve vessels down to 100 μm in diameter

mask



live



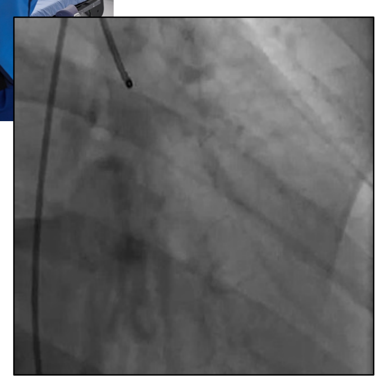


subtracted



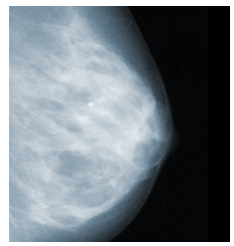
# X-Ray Fluoroscopy

- Continuous real-time imaging
- Used for placements of stents, catheters, pacemakers and other interventional surgery
- Must use low tube current to keep dose reasonable - special detection requirements



## Mammography

- Screening for breast cancer
- Breast compressed
- Magnification 1.5x to 2x
- Low energy x-rays (~ 25 -35 kVp)
- Mb anode x-ray tube (17.5 and 19.6 keV char. x-rays)
- Low dose





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## Some Common Clinical Applications of Planar X-Rays

- Dental x-rays
- Mammography
- Lung disorders and diseases
- Orthopaedics
- Sports injuries and accidents
- Vascular disease (angiography)
- Image-guided interventions (fluoroscopy)



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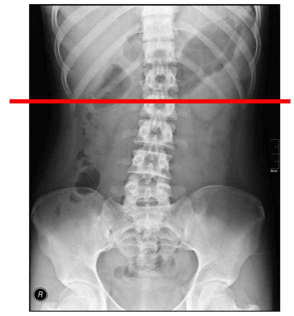
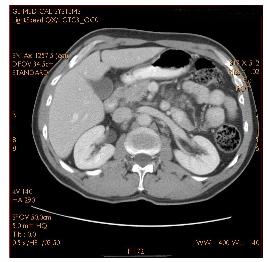
# Computed Tomography (CT)

## also known as

# Computed Axial Tomography (CAT)

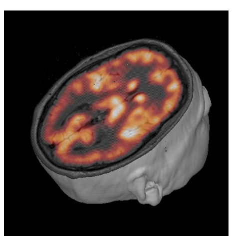


planar x-ray



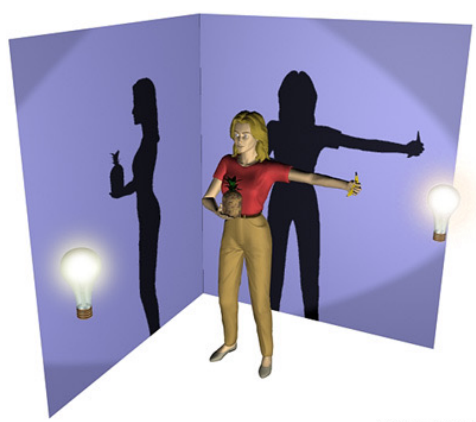
CT scan



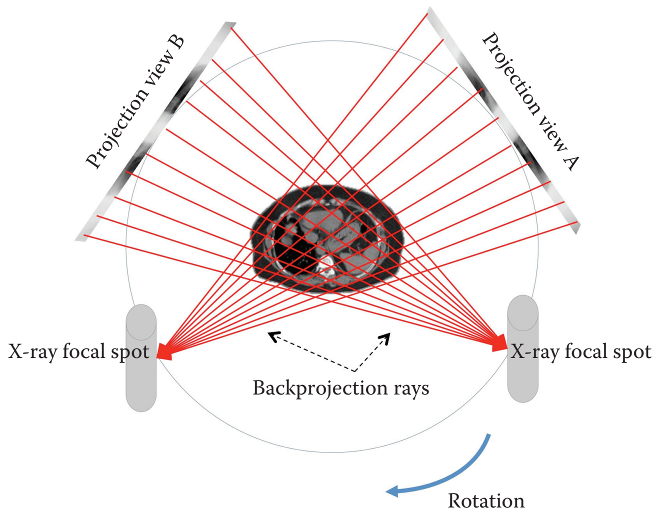


# Computed Tomography

- Produces images of slices through the body
- Imaging system takes views at different angles around the patient and reconstructs the images using mathematical algorithms



# Computed Tomography (CT) Projection Views



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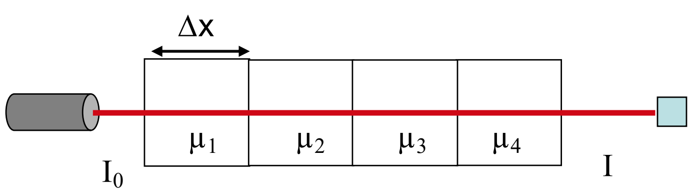
# Converting Projection Data to be linear with μ




$$I = I_0 \exp(-\mu_1 \Delta x) \times \exp(-\mu_2 \Delta x) \times \exp(-\mu_3 \Delta x) \times \exp(-\mu_4 \Delta x)$$
$$= I_0 \exp - (\mu_1 + \mu_2 + \mu_3 + \mu_4)\Delta x$$

$$\ln \frac{I_0}{I} = (\mu_1 + \mu_2 + \mu_3 + \mu_4)\Delta x$$

$I_0$ - x-ray signal with nothing in the scanner

I – x-ray signal measured with patient in scanner



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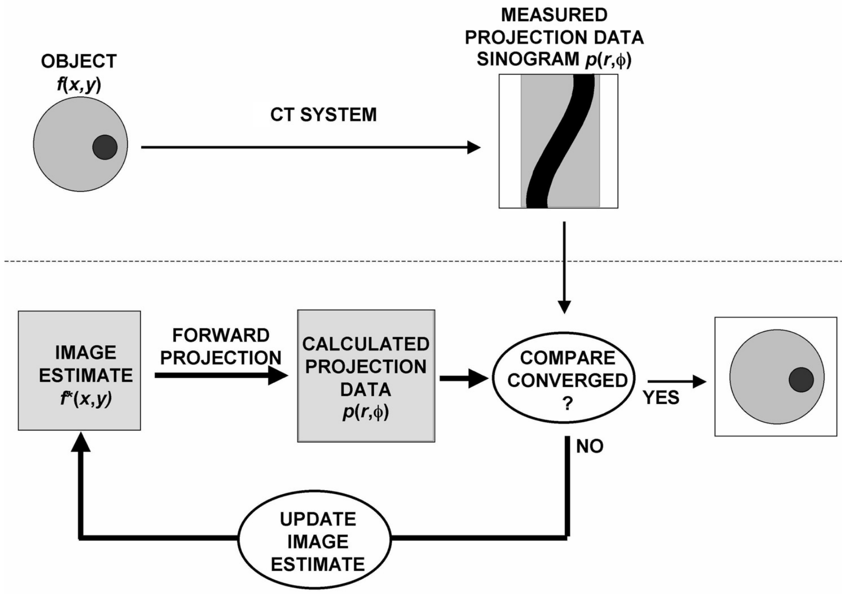
# Iterative Reconstruction Methods



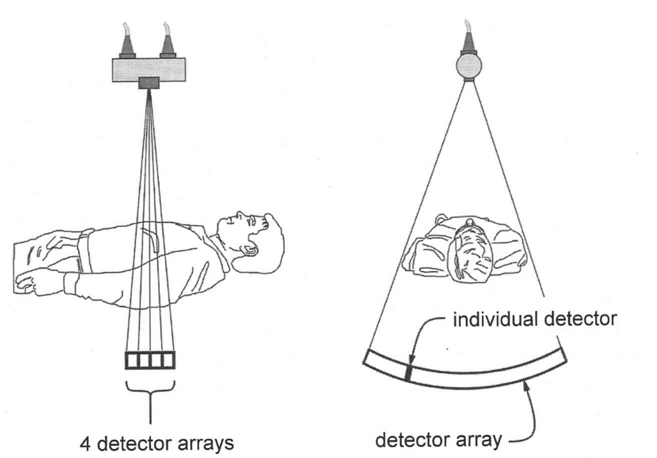




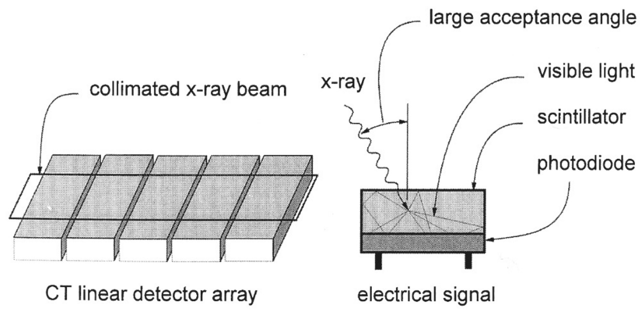

# Typical X-ray CT Scanner

## Multiple Detector Array

- Makes efficient use of x-ray flux by acquiring multiple slices at once



# CT Detectors
# Solid State Detectors




- Ceramic scintillator coupled to photodiode
- Scintillator converts x-ray to visible light
- Photodiode converts light into current



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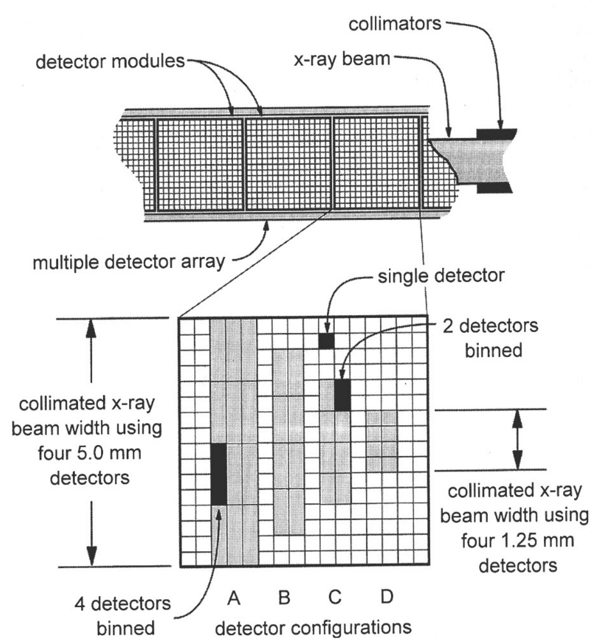
# Detector Array for CT

- Slice thickness and number of slices determined by detector binning and collimation



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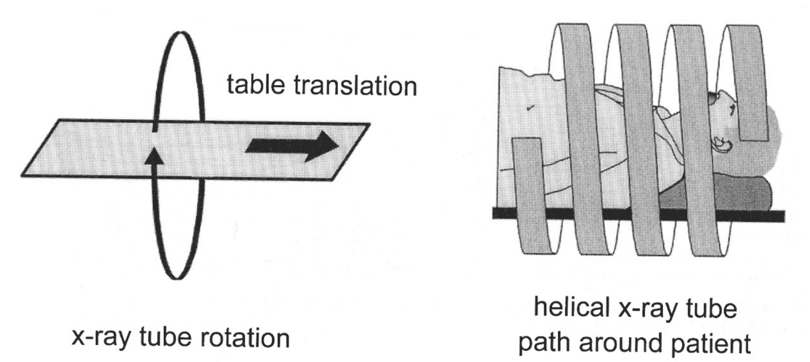
# Helical Scan Acquisition



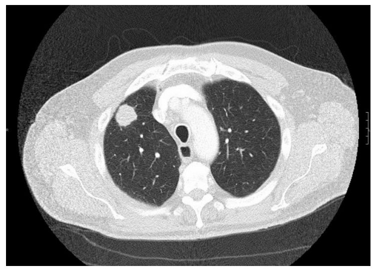

Data acquired while patient bed is moving continuously. X-ray source moves in a helical pattern about patient.

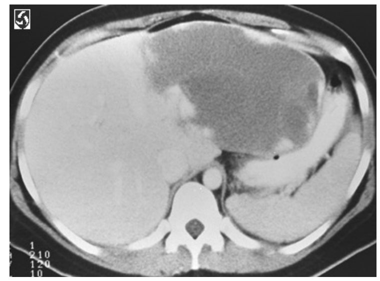


# Typical X-ray Tube Parameters for CT

- Tube potential
  - 80-140 kV
- Tube current
  - 20-500 mA
- Filtration
  - 2-3 mm Al
- Current modulation reduces x-ray flux for low attenuation regions

# Clinical CT scans

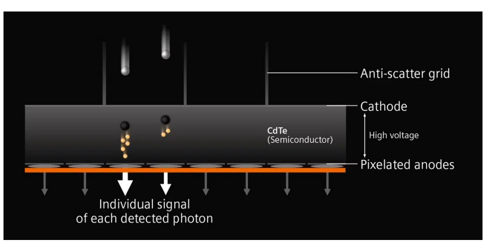




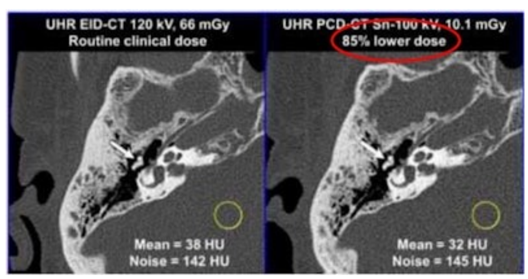




# Photon Counting CT




Courtesy Siemens




Courtesy Dr. Cynthia McCollough, Mayo Clinic

Lower noise, higher contrast
Dose reduction possible
Higher spatial resolution
Multispectral – material decomposition

# X-ray and $\gamma$-ray Radiation Dose

- Absorbed dose (*D*) defined as energy deposited per unit mass
  - 1 Gray (Gy) = 1 J/kg





# Effective Dose

- Attempts to factor in radiation sensitivity of different organs and type of radiation involved

$$E = \sum_{T} w_T \times D_T \times W_R$$

- $W_R$ = 1 for x-rays and gamma rays
- Unit of *E* is the sievert (Sv)

# Tissue Weighting Factors

1

| Tissue | $w_T$ | $\Sigma\, w_T$ |
|---|---|---|
| Active bone marrow, Colon, Lung, Stomach, Breast, Remainder tissues: mean equivalent dose* | 0.12 | 0.72 |
| Gonads | 0.08 | 0.08 |
| Bladder, esophagus, liver, thyroid | 0.04 | 0.16 |
| Endosteal tissues, brain, salivary glands, skin | 0.01 | 0.04 |
| **Total** | | **1** |

* Remainder tissues are adrenal glands, extrathoracic airways, gallbladder, heart, kidneys, lymphatic nodes, skeletal muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, and uterus/cervix (♀). ICRP publication 103 (2006)





# A Quick Quiz – Effective Dose

- Annual dose for US domestic pilot in 1 year
- Abdominal/pelvic CT scan
- Annual dose from natural potassium in the body
- Mammogram
- Annual natural background in Denver, CO

# Effective Dose for Diagnostic Exams

American College of Radiology
Dose Reference Card

| | Procedure | Approximate effective radiation dose | Comparable to natural background radiation for |
|---|---|---|---|
| ABDOMINAL REGION | Computed Tomography (CT) — Abdomen and Pelvis | 10 mSv | 3 years |
| | Computed Tomography (CT) — Abdomen and Pelvis, repeated with and without contrast material | 20 mSv | 7 years |
| | Computed Tomography (CT) — Colonography | 6 mSv | 2 years |
| | Intravenous Pyelogram (IVP) | 3 mSv | 1 year |
| | Radiography (X-ray) — Lower GI Tract | 8 mSv | 3 years |
| | Radiography (X-ray) — Upper GI Tract | 6 mSv | 2 years |
| BONE | Radiography (X-ray) — Spine | 1.5 mSv | 6 months |
| | Radiography (X-ray) — Extremity | 0.001 mSv | 3 hours |
| CENTRAL NERVOUS SYSTEM | Computed Tomography (CT) — Head | 2 mSv | 8 months |
| | Computed Tomography (CT) — Head, repeated with and without contrast material | 4 mSv | 16 months |
| | Computed Tomography (CT) — Spine | 6 mSv | 2 years |
| CHEST | Computed Tomography (CT) — Chest | 7 mSv | 2 years |
| | Computed Tomography (CT) — Lung Cancer Screening | 1.5 mSv | 6 months |
| | Radiography — Chest | 0.1 mSv | 10 days |
| DENTAL | Intraoral X-ray | 0.005 mSv | 1 day |
| HEART | Coronary Computed Tomography Angiography (CTA) | 12 mSv | 4 years |
| | Cardiac CT for Calcium Scoring | 3 mSv | 1 year |
| MEN'S IMAGING | Bone Densitometry (DEXA) | 0.001 mSv | 3 hours |
| NUCLEAR MEDICINE | Positron Emission Tomography — Computed Tomography (PET/CT) | 25 mSv | 8 years |
| WOMEN'S IMAGING | Bone Densitometry (DEXA) | 0.001 mSv | 3 hours |
| | Mammography | 0.4 mSv | 7 weeks |



# Ultrasound

# Ultrasound – Basic Properties

Advantages
- portable
- real-time
- no ionizing radiation
- fetal imaging
- inexpensive

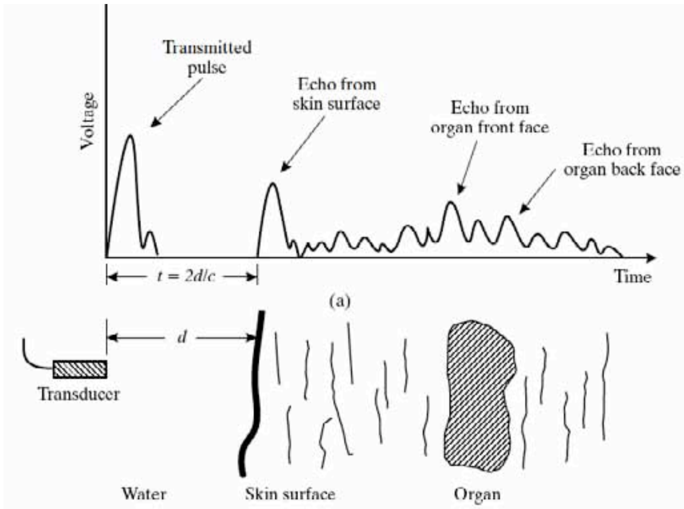





# Ultrasound Characteristics

- Produces images via backscattering of mechanical energy from boundaries between tissues
- Frequency: typically 1 to 10 MHz
  - Use lower frequencies for deep-lying structures
  - Higher frequencies for superficial structures
- Real-time: 30 frames/second
- Velocity = 1540 m/s in water and soft tissues
- Wavelength = 0.3 mm in water at 5 MHz

# Basic Principles of Ultrasound Imaging








# Ultrasound Systems

# Major Clinical Applications

- Obstetrics and gynecology
  - Fetal health
- Cardiac function
- Intra-abdominal imaging
  - Liver, kidneys, spleen and gallbladder
- Musculoskeletal applications
- Compromised flow in veins and arteries
- Tracking of needle biopsies



# Example Images


# Single Crystal Transducer

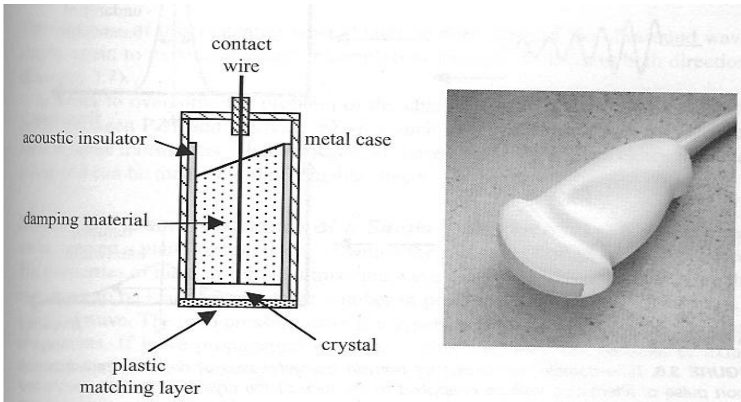



*FIGURE 3.5. (Left) A simple schematic of a single-crystal transducer. (Right) A photograph of a commercial transducer (©2000 ATL Ultrasound).*



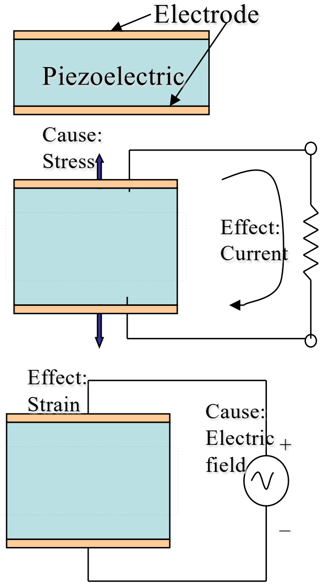
# Piezoelectric Crystal

- Commonly lead zirconate tungstate (PZT)
- Two faces of crystal coated with a thin layer of silver as electrodes
- Usually a disk which is flat or concave (for focused transducer)
- Crystal resonant frequency

$$f_0 = \frac{c_{crystal}}{2d}$$

  – $c_{crystal}$ – speed of sound in crystal (~4000 m/s)
  – $d$ is crystal thickness

# Piezoelectric Effect



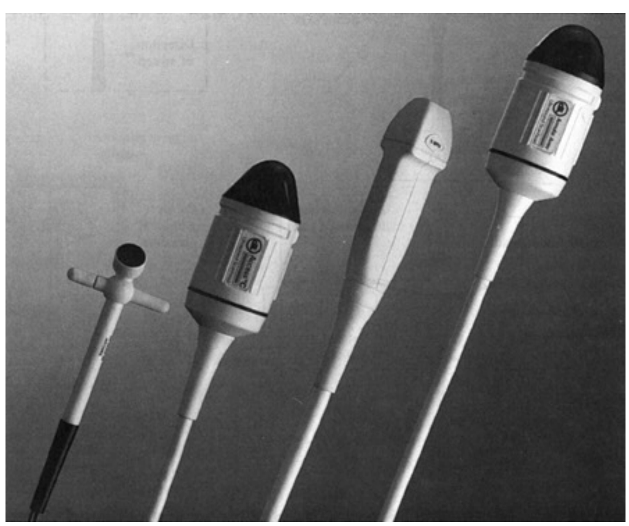

Unstrained piezoelectric material

***The direct piezoelectric effect.*** An applied stress results in the generation of electric charge. The charge is proportional to the stress magnitude and direction. An example is a barbecue igniter.

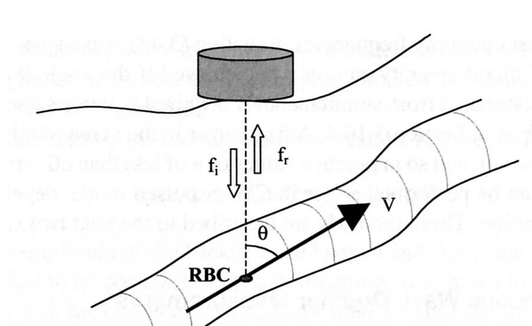
***The converse piezoelectric effect.*** An applied electric field results in a strain. The strain is proportional to the field direction and magnitude. An example is a buzzer used in a pager.



# Ultrasonic Transducers



# Doppler Effect




$$f_i = \frac{c}{\lambda}$$

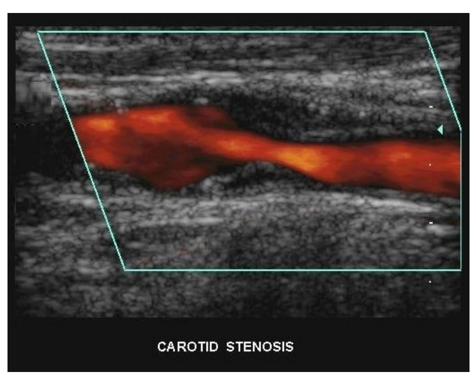
$$f_{RBC} = \frac{c + v\cos\theta}{\lambda}$$

$$\Delta f_{RBC} = f_{RBC} - f_i = \frac{f_i v \cos\theta}{c}$$

$$\Delta f = \frac{2 f_i v \cos\theta}{c}$$



# Color Doppler Imaging

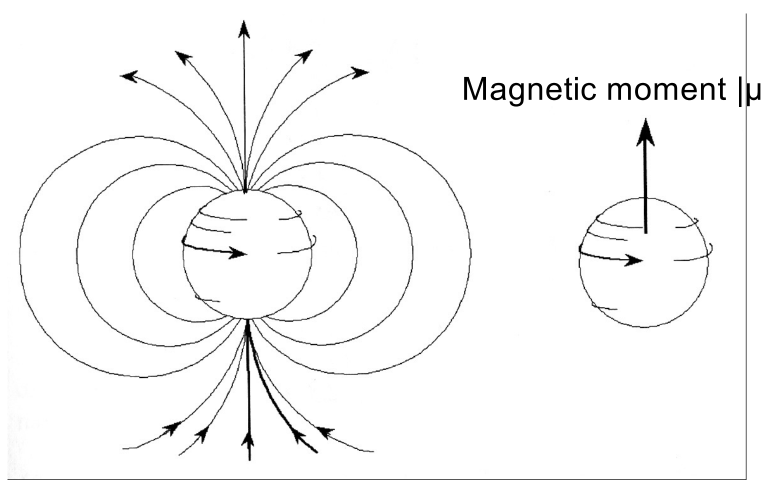
# Magnetic Resonance Imaging (MRI)





# Proton Spin and Magnetic Moment

- Protons possess a property known as spin
- Can be visualized classically as proton spinning around an axis



# Basic Information

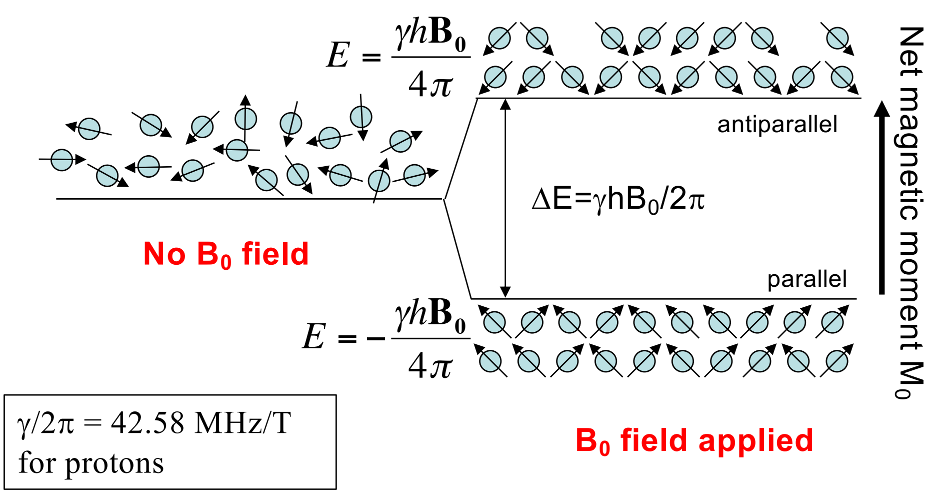
- MRI primarily detects signals from protons (water, lipids)
- 1 liter water ~ $3 \times 10^{26}$ protons
- Human body: 70% is water

- 1 Tesla = 10,000 Gauss
- MRI magnet strengths, 0.2 T up to 11 T
- Earths magnetic field: 50 μT

- Can explain MRI using two approaches
  - Quantum mechanical description
  - Classical description



# Ensemble of Protons in a Magnetic Field



## Some Numbers

Compute ΔE (assume protons and $B_0$=1.5T)

$$\Delta E = \frac{\gamma h \mathbf{B}_0}{2\pi} = (42.58 \times 10^6) \times 1.5 \times (6.63 \times 10^{-34}) = 4.2 \times 10^{-26}\ \mathrm{J}$$

Where is this in electromagnetic spectrum?

$$f = \frac{E}{h} = \frac{\gamma \mathbf{B_0}}{2\pi} = (42.58 \times 10^6) \times 1.5 = 63.9\mathrm{MHz}$$

*f* is called the Larmor frequency



## Population of Energy Levels

$$\frac{N_{antiparallel}}{N_{parallel}} = \exp\left(-\frac{\Delta E}{kT}\right) = \exp\left(-\frac{\gamma h B_0}{2\pi kT}\right)$$

T = temperature (K)
k = Boltzmann constant 1.38 x $10^{-23}$ J/K
h = Planck's constant 6.63 x $10^{-34}$ Js
ΔE = difference in energy levels

## Some More Numbers…

What is relative population of two energy levels for protons at 1.5T and at room temperature?

$$\frac{N_{antiparallel}}{N_{parallel}} = \exp\left(-\frac{\Delta E}{kT}\right) = \exp\left(-\frac{\gamma h B_0}{2\pi kT}\right) = 0.999990$$

So only ten parts in a million difference between population of two energy states.

But 1 $mm^3$ (1 μL) of tissue contains ~ 3 x $10^{20}$ protons, so this are still 3 x $10^{15}$ protons more in lower energy state than higher energy state.



## Larmor Frequency

The Larmor precession frequency $f_0$ is the frequency of the electromagnetic field that must be applied for transitions to occur between the parallel and antiparallel energy levels

$$\Delta E = \frac{\gamma h B_0}{2\pi}$$

$$f_0 = \frac{\gamma B_0}{2\pi}$$

# How is the signal in MRI obtained?

- Need to produce changing magnetic field.  This can induce a current in a coil (so far net magnetic moment is stationary)
- To do this, we can"tip" some magnetization into the x-y plane
- Accomplished by using a second magnetic field orthogonal to $B_0$ with a frequency given by the Larmor frequency

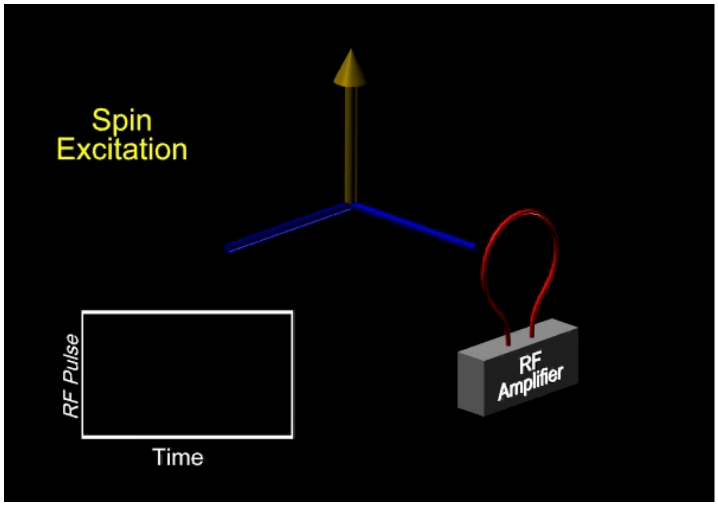




# Application of $B_1$ Field

- In MRI, an additional magnetic field, called the $B_1$ field is applied
- This field is applied in the transverse x-y plane
- It is a time-varying field with a frequency equal to the Larmor frequency $f_0$
- This can excite spins from parallel to anti-parallel orientation, changing the magnitude of $M_z$

# Creating the Signal

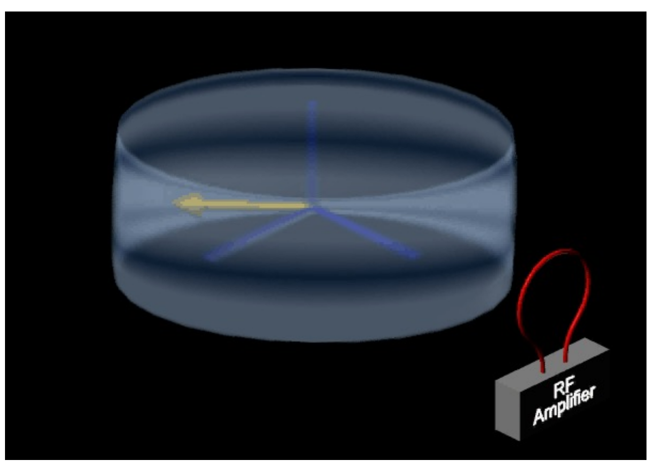



©The Animated Physics of MRI, by Donald Plewes





# Detecting the Signal

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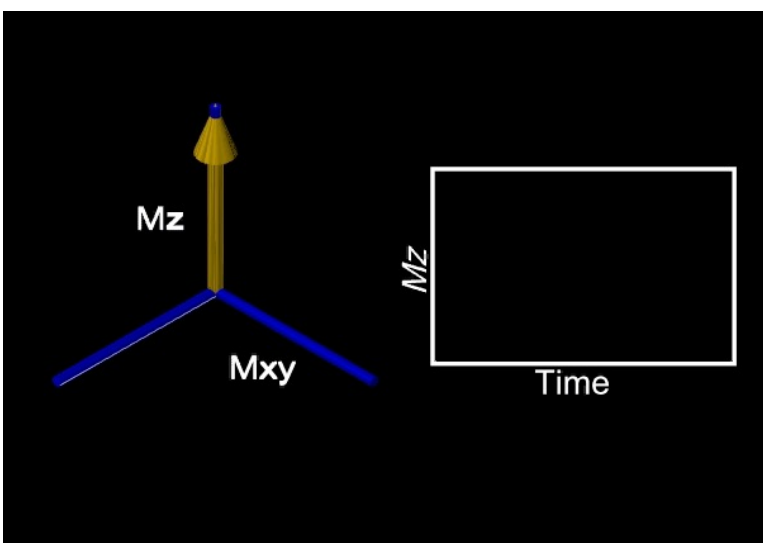
# Signal Decay

- After application of pulse, MRI signal does not stay constant, but actually decays away.
- RF pulse transfers energy from coil to protons, resulting in non-Boltzmann distribution of population of states
- Each of the components of magnetization will return to their equilibrium values over time



# $T_1$ and $T_2$ Relaxation



# Tissue $T_1$ and $T_2$ values

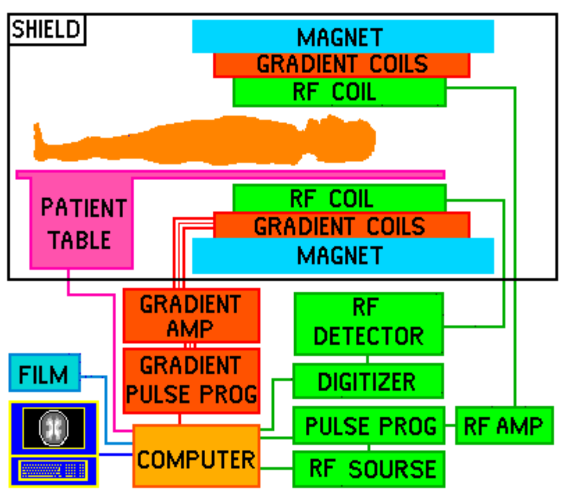
**TABLE 4.2. Tissue Relaxation Times at 1.5 T**

| Tissue | $T_1$ (ms) | $T_2$ (ms) |
|---|---|---|
| Fat | 260 | 80 |
| Muscle | 870 | 45 |
| Brain (gray matter) | 900 | 100 |
| Brain (white matter) | 780 | 90 |
| Liver | 500 | 40 |
| Cerebrospinal fluid | 2400 | 160 |





# Components of MRI Scanner



# Magnets

- **Permanent Magnet**
  - For fields up to ~ 0.35 Tesla
  - Relatively low cost, no cooling required, limited stray field
  - Open systems can be designed (patient is in-between the two poles)
  - Problem: field homogeneity and stability depends on room-temperature

- **Resistive Magnets**
  - For fields up to ~ 0.35 Tesla
  - Constant current (*i*) through a conductor $B_0 \sim i$
  - Resistance of conductor causes heat
  - Problem: field homogeneity and stability depends on room-temperature

- **Superconducting Magnets**
  - At very low temperatures, resistance of conductor → zero!
  - Works usually without power consumption (once the current has been fed in, it runs forever if the temperature is low enough (<10 K).
  - Superconducting coil (special alloy) is embedded in liquid nitrogen, vacuum, and helium.
  - Shim coils are used to fine-tune the field homogeneity.



# Gradient Coils

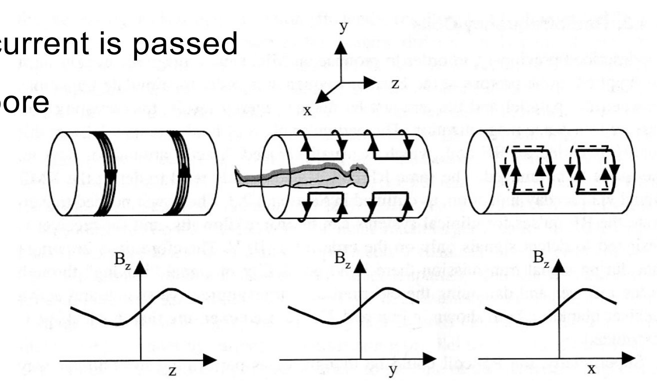
Used to alter Larmor frequency vary as a function of location -> imaging

Field strength small compared with main field (~20-40 mT/cm)

Can use conventional conductors (copper) at room temperature (water cooled for heat dissipation)

Consist of loops of wire through which current is passed

Cylindrical geometry to match magnet bore



# RF-Coils

Head RF-coil
(volume coil)



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# Instrumentation
# Clinical MRI Scanner

Low-field system 0.35 T (Siemens)

Avanto 1.5 T (Siemens)



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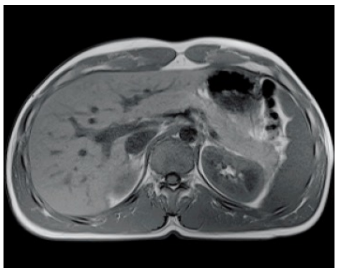
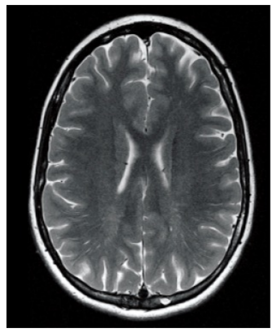
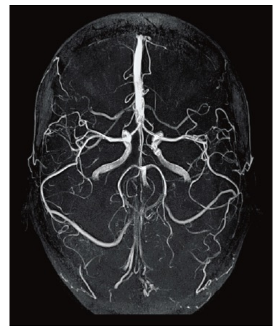
# 1.5 T Clinical MRI Images



T1 weighted
Multi breath-holding
1.5 T Magnetom Avanto



T2 weighted
1.5 T Magnetom Avanto



T2 weighted Angio
1.5 T Magnetom Avanto